Heavy Fermions in a Dilute Limit

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One of the challenges of modern condensed matter physics is to explain the behavior of a large class of metals, called heavy fermion materials, which contain rare-earth elements. Electrical current in these materials is carried by massive particles, called heavy fermions. We aim to assess the applicability of the standard model of heavy fermion systems. The model assumes that the main source of heavy fermion behavior are interactions of a rare-earth ion with normal electrons. Our investigation of the first discovered heavy fermion material $CeAl_3$ combined with a normal metal $LaAl_3$, demonstrates that standard model needs to be augmented and provides important information on how to incorporate important interactions between different rare earth ions. These results will serve as the input for the next generation of the heavy fermion theory.

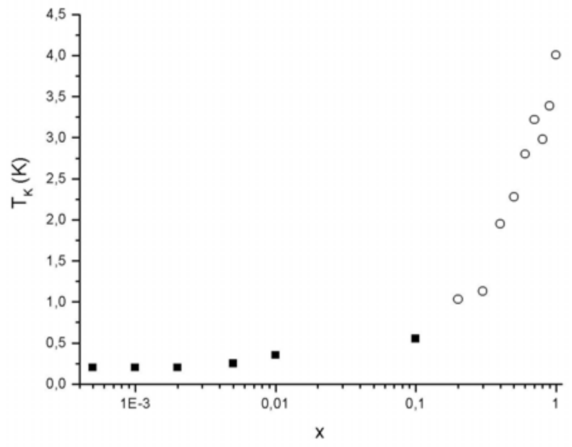

Fig. 1. Kondo temperature (inversely proportional to heavy fermion mass) versus Ce concentration in $Ce_xLa_{1-x}Al_3$

1. C. R. Rotundu et al., Phys. Rev. Lett., cond-mat/0404595.

There is a great quest to understand one of the most fascinating states of matter, a heavy fermion state. Electrical current in these states is carried by massive particles (heavy fermions), hundreds times heavier than the electron. The principle ingredient of heavy fermion metals are rare earth elements, such as Cerium, Ytterbium or Uranium. We have performed a dilution study of the first discovered and canonical heavy fermion metal $CeAl_3$. High quality alloys were prepared by mixing $CeAl_3$ with a normal metal $LaAl_3$ in a wide range of proportions. Physical properties of these alloys were measured at temperatures as low as 0.03 degree above the absolute zero. We have found that the mass of these heavy particles strongly depends on the concentration (T_K in Fig. 1 is inversely proportional to the heavy fermion mass), and therefore the distance between two nearest Ce ions. Thus, we conclude that interactions between different rare earth ions have to be taken into account in the theory of heavy fermions. Current model of the heavy fermion state (based on the so-called single impurity Kondo model) neglects these interactions. Our findings suggest important directions for the next generation of the heavy fermion theory and future work in this area.

This work has been submitted to the Physical Review Letters.

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Education

A graduate student (Costel Rotundu) and postdoctoral associate (Hiryoki Tsujii) participated in this project. They synthesized and characterized high quality samples. They performed specific heat measurements in the National High Magnetic Field Laboratory in Tallahassee. Tsujii is currently an Assistant Professor at Low Temperature Physics Laboratory, RIKEN, Wako, Saitama Japan.

Costel Rotundu is still with us working toward his Ph.D.

Broader impact

Heavy fermions is a fascinating state of matter resulting from strong electron correlations. Other manifestations of electronic correlations include technologically important magnetic materials and superconductors. Heavy fermions provide a fertile ground to test new theories and models of electronic correlations that can be applied to a broad spectrum of materials.

These theoretical predictions can be most readily tested at very low temperatures and high magnetic fields. In addition, these experiments provide input for the next generation models and theories of condensed matter.